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Surf or turf: A shift from feed to food cultivation could reduce nutrient flux to the Gulf of Mexico

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Abstract

The extensive use of nitrogen fertilizer on the central U.S. croplands contributes to nitrogen loading by the Mississippi River and the development of seasonal hypoxia in the Gulf of Mexico. The majority of grains cultivated on central U.S. croplands are used as animal feed, rather than directly as human food. In this study, the IBIS-THMB nitrogen modeling system is used to demonstrate how a shift away from meat production from Mississippi Basin crops could reduce total land and fertilizer demands by over 50%, without any change in total production of human food protein. The change would return nitrate-nitrogen export by the Mississippi River to levels at which the Gulf of Mexico "dead zone" has been small or non-existent. An analysis of future land use scenarios and other mitigation proposals, including the construction of riparian wetlands, indicates that a reduced focus on beef production may need to be a part of nitrogen management policy in the Mississippi Basin.

Keywords: Nitrogen; Mississippi River; Gulf of Mexico; Hypoxia; Fertilizer; Vegetarian diet

1. Introduction

The dramatic increase in nitrogen (N) fertilizer use in the U.S. over the past half century contributed to a tripling of crop yields (Goolsby et al., 2000). The use of N-fertilizer on dominant crops in the central US like corn is commonly blamed for almost tripling the flux of nitrogen by the Mississippi River to the Gulf of Mexico (Goolsby et al., 2000; Donner et al., 2004a). The large influx of nitrogen, largely in the form of nitrate (NO_3^-), helps fuel the development of bottom-water hypoxia on the continental shelf of the northern Gulf of Mexico each summer, threatening fisheries yields and community structure (Turner and Rabalais, 1994; Rabalais et al., 1996). A 30–50% reduction in nitrate export by the Mississippi may be necessary to minimize the size of the annual hypoxic zone (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001; Scavia et al., 2003).

Over 70% of the grain produced from the dominant Mississippi Basin crops like corn is now employed in animal production (US Department of Agriculture (USDA), 2004a). Despite large advances in modern animal husbandry and feed science over recent decades, the efficiency with which feed grains are converted to human-edible meat protein is relatively low for most forms of meat production, especially grain-fed beef, due to physiological constraints (Smil, 2001, 2002a). Conventional wisdom suggests that adopting diets with less meat consumption—"eating lower on the food chain"—could reduce crop production requirements and the environmental impact of agricultural chemical use (Smil, 2002a; Howarth et al., 2002; Galloway et al., 2003). Devoting Mississippi Basin croplands to feed cultivation, rather than food cultivation, may be a cause of the large annual flux of nitrogen to the Gulf of Mexico and the development of the seasonal hypoxic zone. Yet the role of food production and dietary choices in the Mississippi nitrogen and Gulf hypoxia problem has never been specifically evaluated.

In this study, I take advantage of US agricultural inventory data and the new IBIS-THMB nitrogen

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modeling system to quantify how a theoretical shift from feed to food cultivation would impact nitrate export to the Gulf of Mexico. First, the cropland and fertilizer required to produce enough vegetable and dairy protein to replace the meat (beef, poultry and pork) protein produced by Mississippi Basin feed is estimated from USDA inventory data, standard agricultural practice information and dietary data. Second, the IBIS-THMB modeling system is used to simulate how such a theoretical shift away from meat or red meat production would impact nitrate export by the Mississippi River and the likelihood of hypoxia developing in the Gulf of Mexico. Finally, the modeling system is used to evaluate the importance of dietary transition in a successful nutrient management policy, in light of other mitigation proposals, recent dietary trends and future land use projections.

2. Animal feed cultivation in the Mississippi Basin

Crop production and fertilizer use statistics were used to estimate the area of land and amount of fertilizer used in the cultivation of the six primary feed crops (corn, soybeans, sorghum, barley, oats and wheat) in the Mississippi Basin (Table 1). The annual land area, crop production and agricultural chemical use for the six major feed crops across the Mississippi Basin were determined from USDA 2000–2002 county-level data on crop production and planted area (USDA, 2004b), 2000–2002 state-level on fertilizer application rates (USDA, 2001, 2002, 2003a), and a $5' \times 5'$ spatial resolution ($\sim 7 \times 9$ km) map of the Mississippi Basin (Donner et al., 2002). The county-level crop production and planted area data covers all the producing states for the six feed crops. The fertilizer surveys cover the major producing states for each crop (e.g., 96% of all maize produced); where no data was available, the area-weighted mean application rate for the reporting Mississippi Basin states was adopted. Nationally averaged application rates were used for barley, oats and sorghum (Food and Agriculture Organization (FAO), 2002) since complete state-level data are not available.

The data shows that corn and soybeans are the prominent feed crops, comprising 94% of the production of the major feed crops in the Mississippi Basin (Table 1). Corn alone receives the majority of the nitrogen (73%), phosphorus (62%), potash (64%) and herbicide (62%) applied to the six feed crops, because of the extensive cultivation and typically high application rates. Soybeans cover an equally large land area, but receive only 2% of the nitrogen fertilizer on the feed crops, because the soybean plant can acquire much of the nitrogen needed for growth via fixation.

The total production of animal feed from these crops was determined from the fraction of each crop sold as feed in the US, using the same feed to food ratio among exports (USDA, 2004a). Analysis of US agriculture trade data (USDA, 2005a) and feed usage in major importing countries (FAO, 2005) indicates that the food to feed ratio is similar domestically and among major importing countries (e.g., the US uses 74% of corn for feed; the seven countries receiving the majority of US exports use 63% of corn for feed). In addition to the actual feed grains, it was assumed that 50% of feed crop residues are also used as feed (Council on Agricultural Science and Technology (CAST), 1999). The total animal feed produced from residue was estimated from the average residue fraction of feed crops (55% residue, 45% grain) and the dry matter content of each crop (CAST, 1999). Since the digestible energy and protein in crop residues is typically one-third that of feed grains (Loomis and Connor, 1992), each three kg of residue feed was treated as equivalent to 1 kg of grain feed.

The total estimated feed grain and residue production from the six crops in the Mississippi Basin is 255 million tons per year, of which 72% comes from corn cultivation. A fraction of all food and feed is lost or spoiled during transport and manufacturing; for example, the USDA estimates that 29% of US food production is lost via spoilage, cooking, plant waste and other losses. Here, the total loss and spoilage rate of 34% used in other large-scale studies (Imhoff et al., 2004), is applied. The resulting estimate is that 169 million tons per year of feed grains grown in the Mississippi Basin that used in meat production. Sensitivity analysis shows this total ranges from 155.3 to 182.4 million tons, depending upon the

Table 1
Production, land area and nutrient use for six major feed crops in the Mississippi Basin

Crop	Land area (10^6 ha)	Production (10^9 kg)	Sold for feed[a] (%)	Nutrient use (10^6 kg)		
				Nitrogen	Phosphate	Potash
Corn	24.2	211.2	74	3595	1254	1460
Soybean	24.1	64.4	73	97	294	545
Wheat	13.1	31.0	18	841	307	128
Sorghum	2.4	8.6	83	279	112	112
Barley	0.5	1.0	70	38	15	8
Oats	0.6	1.4	37	107	45	18

[a]Assumes same fraction for domestic and exports and that 98% of soybean meal is used for protein feed (USDA, 2004a). Production reported in fresh mass, converted from yield units. Nutrient use reported as elemental mass (N, P, K).

assumptions about the fraction of exports and residue used for feed (see Table 3). The fraction of feed lost or spoiled obviously also impacts the total feed production; however, since the same fraction is also used to estimate total food production in the alternate diet scenarios, it has no impact on the final results of the study.

3. Meat production from Mississippi Basin feed

The amount of meat and meat protein produced from feed grown in the Mississippi Basin croplands was determined from the feed production, the distribution of feed between the primary animal production systems and feed to food conversion rates based on standard US agricultural practices. This approach provides an estimate of the contribution of Mississippi Basin feed crops to meat production, regardless of whether that meat production occurred within the Mississippi Basin. The US meat production data was not used directly because it includes the contribution of non-feed grain components of the animal diet and feed cultivated outside the Mississippi Basin but excludes meat produced outside the US with feed cultivated in the Mississippi Basin.

The vast majority of US feed grains (>99%) are used in beef, pork, poultry and dairy production (USDA, 2003b). The amount of Mississippi basin feed devoted to dairy production (19 million tons) was estimated from the fraction of dairy feed use, reported using a USDA metric based on the feed consumed by an average dairy cow, to total domestic feed use (USDA, 2003b). The distribution of the other 149 millions tons of feed between beef, pork and poultry production was determined from the 2000–2002 US total meat production data and the food-feed conversion ratios calculated from US feed use and animal production statistics (Smil, 2001, 2002b; USDA, 2004a).

The results indicate that 63% of the non-dairy feed is allocated to beef production, with 16% devoted to poultry production. For comparison, the distribution of feed use was also determined directly from the estimated rates of feed use in the different animal production systems (USDA, 2003b). This alternate method suggests only 32% of the non-dairy feed is allocated to beef and 39% to poultry. The predicted meat production with the alternate feed distribution, however, is unrealistic; beef production is half the reported US total, while poultry production is twice the reported US total (USDA, 2004a). The initial method was adopted as the baseline for this study because it provides the best representation of meat production from Mississippi Basin feed.

The total edible weight and edible protein of beef, poultry and pork produced from Mississippi Basin feed was estimated from ratios of feed use, edible weight gain and protein content determined from annual US production data (Smil, 2002b). The results suggest that 11.5 millions tons of edible meat or 2.0 million tons of protein is produced annually from these six Mississippi Basin feed crops (Table 2). Poultry accounts for the majority (57%) of the total protein production, followed by beef (22%) and pork (21%), because of higher feed to food conversion efficiency and protein content. The total estimated meat production from the Mississippi Basin is only 61% of annual mean US production for 2000–2002 (USDA, 2004a), since it includes only the contribution of Mississippi Basin feed to meat production and excludes animal weight gain from grazing and lesser components of feed. Sensitivity analysis indicated that the total edible meat production has an uncertainty of $\pm 14\%$ (9.9–12.5 million tons), depending on the assumptions about residue use, exports and feed use for dairy (Table 3 and 4).

Table 2
Estimated meat production from feed crops cultivated in the Mississippi Basin

Production system	Feed use (10^6 kg)	Edible weight (10^6 kg)	Protein (10^6 kg)
Beef cattle	93,857	2961	444
Pork	31,356	2931	419
Poultry	23,658	5633	1127

4. Land cover and fertilizer use with alternative food production

The crop production, land area and agricultural chemical use were estimated for two sets of alternative food production scenarios. In the first set, cultivation was changed to reflect the replacement of meat or red meat (beef + pork) protein produced by Mississippi Basin croplands to vegetable protein derived from the same original feed crops. In the second set, the meat or red meat protein was replaced by an even mix of corn, soybean, wheat and dairy protein, reflecting the typical cereal, legume and dairy content of a lacto-ovo vegetarian diet (Haddad and Tanzman, 2003; Pimentel and Pimentel, 2003). Crop production was estimated from the protein content of the crops (Loomis and Connor, 1992), again assuming that 34% of production is lost or spoiled during transport and manufacturing. Feed crop production required for the dairy protein was estimated from the ratio of feed use to edible weight gain and the average protein content in US dairy production (Smil, 2002b). The total production of each crop in the alternative scenarios is therefore equal to the initial crop production plus the difference between the crop production required to replace the meat (or red meat) protein and the crop production sold for meat (or red meat) feed.

There is a 53–59% reduction in total demand for the six feed crops in the alternative food production scenarios (Fig. 1). In each scenario, corn and soybeans account for the vast majority (>94%) of the decrease in necessary crop production. Assuming the percent decrease in production of each crop is distributed uniformly to croplands across the Mississippi Basin, the area required for cultivating the

Table 3
Sensitivity analysis

Sensitivity scenario	Grain used for feed (10^6 ton)	Meat product. (10^6 ton)	% decrease in crop product		% decrease in N fertilizer		% decrease in NO_3 export	
			A	B	A	B	A	B
Base case	168.5	11.5	59	47	54	44	51	40
(a) 100% exp. as feed	182.4	12.5	64	51	59	48	55	43
(b) 50% exp. as feed	155.3	10.6	54	43	50	41	47	37
(c) 75% res. as feed	181.1	12.4	58	46	53	44	50	40
(d) 25% res. as feed	156	10.7	60	47	55	45	52	41
(e) 6% feed to dairy	168.5	12.3	58	50	53	47	50	43
(f) 24% feed to dairy	168.5	10.0	60	41	55	39	52	35
(b) + (c) + (e)	166.9	9.9	55	37	50	36	48	32
Alt. feed breakdown	168.5	19.4	52	47	46	45	43	40

Case A: all meat protein replaced with a lacto-ovo diet, case B: only red meat replaced.

six feed crops would decrease by 32–36 million hectares, 10–11% of the entire basin. The reduction in crop production and cropland area would lead to equally large reductions in nitrogen (49–56%), phosphorus (53–61%), potash (57–67%) and herbicide use (55–62%) on the six crops (Fig. 1). The estimated decreases in crop production, land area and fertilizer use are not highly sensitive to the assumptions about residue use, exports and feed use for dairy. In the scenario where all meat protein is replaced with a lacto-ovo diet, the sensitivity analysis shows a range of ±5% for the estimated decrease in crop production and nitrogen fertilizer use.

The greatest reductions in land area and chemical use occur in the scenario where all the meat protein is replaced with protein from the new crop mosaic. The difference between the alternative scenarios, however, is smaller than might be expected because of trade-offs between the protein content of foods, crop nutrient demands and typical crop yields. Since people are less able or willing to consume the high yielding crops fed to ruminants, it is commonly suggested that the cultivation of lower yielding crops to support vegetarian diets may offset land savings from the reduction of feed cultivation. Here, the lacto-ovo vegetarian diet does require the additional cultivation of lower yielding crops like wheat and the cultivation of additional feed for dairy production. However, some of the food produced has high protein content. Therefore, the change to a different crop mosaic to produce a more realistic diet has a small impact on land area requirements. Similarly, keeping poultry in the diet requires only 8–16% more total feed grain, 8–10% more cropland area and 8–10% more nitrogen fertilizer than replacing all meat protein because poultry production has a relatively high feed to food conversion efficiency.

The majority of the reduction in land area and agricultural chemical use in each scenario would likely occur in the Central US corn growing states (Fig. 2). For example, with no feed cultivation for beef and pork production, nitrogen fertilizer on the six feed crops would decrease by 57–58% across most of the Iowa, Illinois,

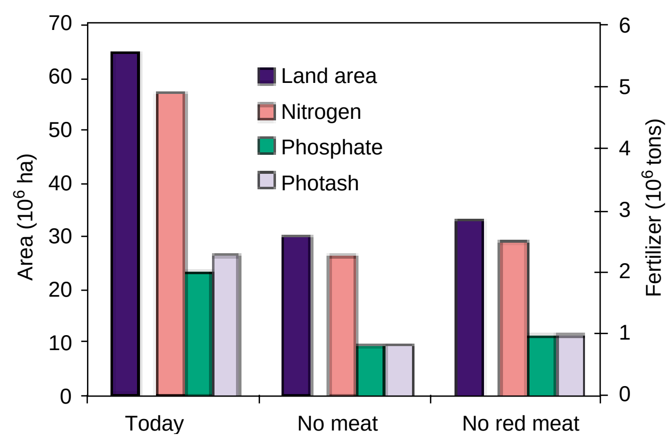

Fig. 1. Estimated land area of the six feed crops and annual N, P and K fertilizer use on those crops for the 2000–2002 period and in the alternate scenarios (with the new crop mix).

Indiana, but less than 20% in Montana and N. Dakota. Fertilizer use in individual regions, or the entire Mississippi Basin, in the alternate scenarios could be lower if the reductions in total crop production were distributed strategically to eliminate lands with lower typical crop yields or N-fertilizer use efficiency.

5. Nitrate export and the development of hypoxia

The impact of the dietary shift on nitrate export by the Mississippi River to the Gulf of Mexico was assessed using the IBIS-THMB dynamic modeling system. The modeling system simulates the movement of water, carbon and nitrogen in natural and agricultural (corn, soybeans and wheat) ecosystems and the transport of water and nitrate through the river system $5' \times 5'$ ($\sim 7 \times 9$ km) spatial resolution (Foley et al., 1996; Coe, 1998; Kucharik et al., 2000; Donner et al., 2004a, b). It has been extensively validated and applied to study crop yields, soil nitrogen cycling, soil moisture, runoff, river discharge, in-stream nitrogen removal and river nitrate flux in the Mississippi Basin (Donner et al., 2002, 2004a, b; Donner and

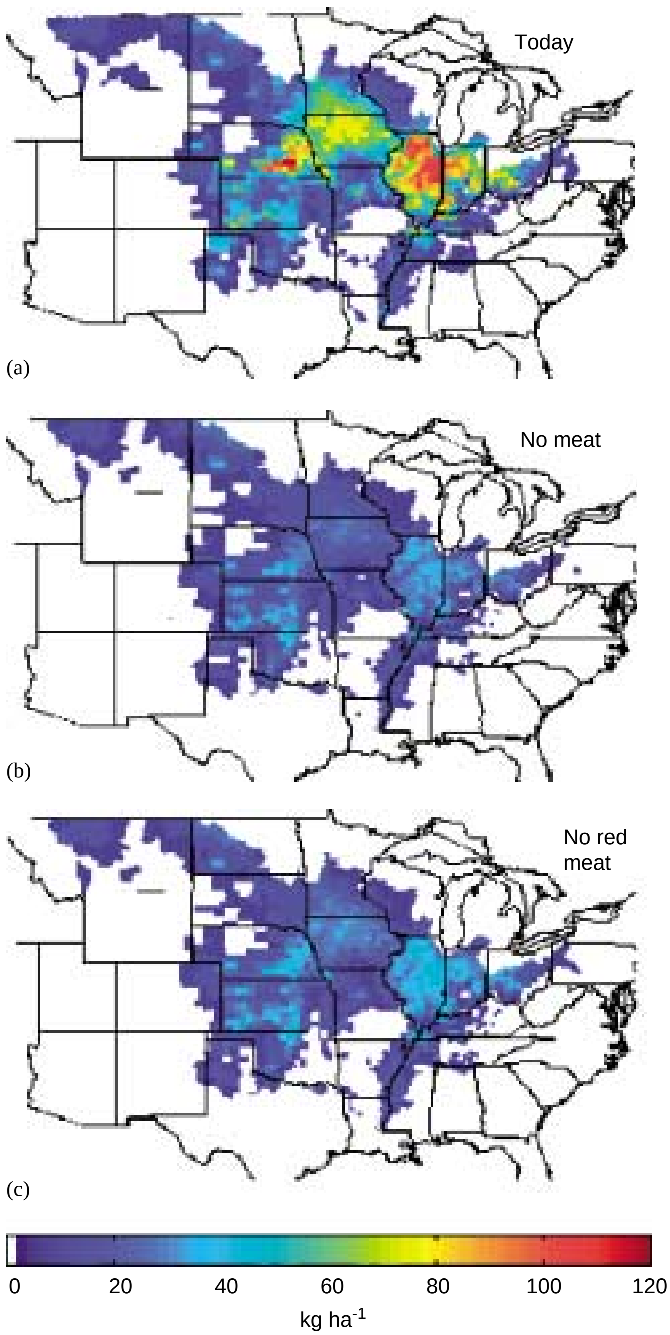

Fig. 2. Annual N fertilizer use (kg ha^{-1} yr^{-1}) on the six crops used as feed in the Mississippi Basin for (a) the 2000–2002 period, (b) the scenario where all meat protein is replaced with food protein from the new crop mix, and (c) the scenario where red meat protein is replaced with food protein from the new crop mix.

Kucharik, 2003; Twine et al., 2004). The simulations in this study were adapted from Donner et al. (2004a), in which IBIS-THMB accurately recreated annual nitrate export by the Mississippi River (from 1960–1994, $r^2 = 0.84$), river discharge and the terrestrial nitrogen budget based on inputs of climate, soil texture, land cover and the primary natural and anthropogenic (fertilizer use, legume cultivation and atmospheric N-deposition) sources of nitrogen. A detailed description of the models and input datasets is available in Donner et al. (2004a).

The alternate diet scenarios were represented by altering the area of cultivation and fertilizer use for each crop in each grid cell. This approach captures the impact of changes in land cover, fertilizer use and legume fixation on soil-N processing, nitrogen leaching to the river system, removal of nitrate during transport downstream removal and the final mass and concentration of nitrate exported to the Gulf of Mexico. The 1985–1994 period was used as a baseline for analysis because it featured a large variability in precipitation, river discharge, nitrate export and the extent of Gulf hypoxia. For comparison to observations, the simulated annual nitrate export is adjusted by the ratio of mean nitrate export in a control simulation and observations.

The simulations suggest that annual nitrate export would decrease by 49–54% if all feed cultivation for meat production was replaced by crops to support a lacto-ovo vegetarian diet. The decrease would be 38–42% if the feed cultivation for only red meat production was replaced (Fig. 3). The results are marginally different than in the scenarios where meat production is replaced with the existing crop distribution—47–51% with all meat, 39–42% with only read meat—due to the trade-offs discussed in the previous section. In each case, the total reduction in nitrate export is highest during the wettest years. For example, with the shift to the lacto-ovo diet, IBIS-THMB predicts nitrate export to be 826,343 ton N less than observed during 1993, the wettest year, but only 263,295 tons N less than observed during 1988, the driest year. However, since the percent decrease in nitrate export varies by only 5% over the 10-year period, the inter-annual variability in nitrate export is still pronounced in the alternate diet scenarios (Fig. 3).

Additional model simulations indicated that the predicted decrease in nitrate export is robust and not highly sensitive to the assumptions (Table 3). For example, the mean annual decrease in nitrate export if all meat protein is replaced with a lacto-ovo diet range from 47% to 55% in the sensitivity simulations. Even using the unlikely alternative feed distribution discussed in Section 3, the mean decrease in nitrate export with no meat consumption lowers to only 43% (Table 3). In general, the simulated decrease in nitrate export could be considered conservative because the modeling system focuses on how the dietary shifts affects fertilizer use and cultivated area. The implied reduction in meat production would also affect manure use, nitrogen loss from hog operations and deposition of nitrogen volatilized from fields.

The results suggest that eliminating meat or only red meat consumption would easily achieve the target of reducing Mississippi nitrogen export by 30% set by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. This target, however, may be optimistic. The impact of nitrogen export reductions on the extent of the hypoxic zone in a given year can only be approximate:

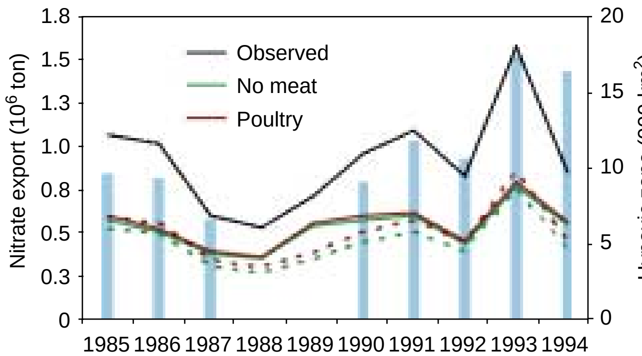

Fig. 3. Annual nitrate export by the Mississippi River at St. Francisville, LA and estimated size of the Gulf of Mexico hypoxic zone from 1985–1994. Simulated nitrate export using IBIS-THMB for the no meat and no red meat scenarios with a lacto-ovo diet are displayed. Observations are based on USGS data (Goolsby et al., 2000). The blue bars represent the estimated annual extent of the hypoxia ($<2\,mg\,O_2\,L^{-1}$) in the Gulf of Mexico. The hypoxic zone was only 40 km^2 in 1988; there is no data for 1989 (Rabalais et al., unpublished data).

the development of hypoxia on the continental shelf also depends upon other factors like mixing due to weather events (i.e., tropical storms) and the availability of other nutrients like phosphorus and silica (Turner and Rabalais, 1994). Some researchers argue a reduction of 40–50% is necessary to account for this variability in climate and oceanographic conditions (Scavia et al., 2003). The 10 year simulation shows that this higher target could be reached by eliminating feed cultivation for all meat, and possibly only red meat, production. The range in the nitrate export between wet and dry years in the alternate diet scenarios demonstrates why climate variability must be factored into nutrient management policy (Donner et al., 2004b).

6. Policy implications

The proposed shift away from the cultivation of feed for meat production is only theoretical. It would require dramatic changes in US agricultural practice and diet that would be difficult to implement and have substantial socioeconomic consequences. However, none of the existing mitigation proposals are expected to achieve the large reduction in nitrogen export necessary to minimize concerns about hypoxia (Keeney, 2002). For example, reaching the lower 30% target through riparian zone management alone would require the construction of at least 2.2 million hectares of highly efficient riparian wetlands, arguably as unrealistic as the proposed dietary shift (Mitsch et al., 2001). Widespread adoption of optimal nitrogen management practices on farms, including better fertilizer timing, soil-N monitoring and planting winter cover crops, could at best achieve a 15–20% reduction in nitrogen inputs to the Mississippi Basin (Howarth et al., 2002). A direct reduction in fertilizer application rates on crops like corn could achieve larger nitrogen loss reductions but at the expense of crop yields (McIsaac et al., 2001; Donner and Kucharik, 2003).

Achieving the required decrease in nitrogen export to the Gulf of Mexico may require combining a more realistic dietary shift with another mitigation proposal. The US Environmental Protection Agency (USEPA) promotes the creation of riparian buffers to reduce non-point source agricultural pollution (USEPA, 2005). Converting the edges of corn and soybean fields to riparian forests or wetlands could reduce nitrogen leaching and help motivate a reductions in feed cultivation. To investigate the combination of riparian zone management and more plausible reductions in feed cultivation, four dietary change scenarios were developed using the SRES future greenhouse gas emissions scenarios (Nakicenovic et al., 2000) and recent US food consumption trends:

1. 26% of beef protein replaced with lacto-ovo diet (SRES B2 in 2050),
2. 35% of beef protein replaced with lacto-ovo diet (SRES B2 in 2100),
3. 20% of beef protein replaced with poultry protein,
4. 50% of beef protein replaced with half poultry/half lacto-ovo diet,
5. 75% of beef protein replaced with one-third poultry / two-thirds lacto-ovo diet.

Scenarios one and two are based on land use changes projected in the SRES B2 future which emphasizes sustainability, including reduced cropland area in developed world due to technology and lower meat consumption (Arnell et al., 2004; Ewert et al., 2005; Rounsevell et al., 2005). Under SRES B2, the area of food and feed crops in the US would decrease by 12% by 2050, and by 19% by 2100 (Strengers et al., 2004). Based on the crop distribution and feed conversion data used in this study, the change in crop area could equate to a 26% decrease in beef consumption by 2050, and a 35% decrease by 2100. The other scenarios are based on the recent trend toward lower per capita beef consumption in the US. Since the 1970s, per capita beef consumption has decreased by 20% and poultry consumption per capita has increased over 40% (USDA, 2005b). Scenario three envisions a continuation of this trend. Scenarios four and five envision aggressive dietary shifts that could come as a result of public attention to the health benefits of reducing beef consumption.

The impact of these scenarios on nitrate export by the Mississippi River was simulated with IBIS-THMB. Additional simulations were used to estimate the impact of combining the dietary change scenarios with the construction of riparian wetlands adjacent to 50% or 100% of the corn and soybean fields in the Mississippi Basin. Field experiments indicate constructed riparian wetlands could remove roughly 30% of the nitrogen leaching from corn or soybean fields in the central US (Mitsch and Day, 2005).

The results indicate that the reduction in nitrate export in the proposed future scenarios will fall well short of the target without the expansion of riparian wetlands

Table 4
Decrease (%) in crop production, nitrogen fertilizer use and nitrate export in the integrated scenarios

Scenario	Crop production	Nitrogen fertilizer	NO_3 export (% riparian land)[a]		
			0%	50%	100%
SRES 2050 (26% beef)[b]	9	13	8	19	31
SRES 2100 (35% beef)[c]	13	16	11	22	32
20% beef→poultry[d]	7	11	6	17	28
50% beef replaced (1)[e]	17	20	15	25	35
75% beef replaced (2)[f]	26	28	22	31	40

[a]Reduction in mean annual nitrate export, as simulated by IBIS-THMB, with riparian wetlands added to 0%, 50% or 100% of corn and soybean land.
[b]26% of beef protein replaced with protein from lacto-ovo diet (SRES B2 in 2050).
[c]35% of beef protein replaced with protein from lacto-ovo diet (SRES B2 in 2100).
[d]20% of beef protein replaced with poultry protein (based on US consumption trend).
[e]50% of beef protein replaced with half poultry/half lacto-ovo diet.
[f]75% of beef protein replaced with one-third poultry/two-thirds lacto-ovo diet.

(Table 4). A 30% reduction in mean annual nitrate export could be achieved in the SRES futures and the aggressive dietary transitions scenarios only if combined with the construction of riparian wetlands adjacent to almost all the corn and soybean land (Table 4). Reaching the 40–50% reduction target would therefore require improvements in fertilizer management or technology, a more dramatic dietary shift (e.g. Scenario 5), higher efficiency of nitrogen removal in riparian wetlands or construction of riparian forests or wetlands adjacent to other croplands (e.g. wheat fields). The results suggest this could occur in a SRES B2 future but is unlikely until the latter half of the century. Any expansion of biofuel production, as anticipated in the SRES scenarios, would also have to either be extremely limited or based on less N-intensive crops. Nitrogen loading in the intervening period would continue to cause ecological damage in the northern Gulf of Mexico and contribute to nitrogen storage in deep groundwater and coastal sediments. In summary, reaching the nitrate export reduction target will a coordination of many different mitigation techniques with a more rapid shift away from beef production than implied by current trends or projected in the SRES scenarios.

7. Conclusions

There is no easy solution to the Mississippi nitrogen and Gulf of Mexico hypoxia problem. The results of this study suggest that reaching the nitrate reduction targets will require some reforms to a food production system that devotes a majority of fertilized croplands to the cultivation of feed grains for low efficiency animal production. The question is whether such reforms are feasible. Feed-based meat production and meat consumption are deeply entrenched in the US economy and culture. Even the more moderate shifts in diet and food production investigated in the previous section would be very difficult to implement solely to address the nitrogen-loading problem.

A shift in diet and food production may be more feasible if part of an integrated effort to address other environmental, human health and economic issues. First, reducing cropland requirements and agricultural chemical use would decrease groundwater pollution and soil erosion, decrease the emissions of N_2O, a powerful greenhouse gas, and NO_x, a precursor to smog. It would also increase opportunities for restoration of native grassland habitats and for carbon sequestration. Second, a shift to diets with lower meat consumption would improve human health and reduce the burden on the health care system. Meat-rich diets, high in cholesterol and saturated fat, have been linked to risk of coronary heart disease, type II diabetes, many forms of cancer and the increase in obesity in the United States (Mann, 2002; Key et al., 2004; Chao et al., 2005). Obesity alone costs the US over $100 billion a year in health care costs and reduced worker productivity (Wolf et al., 2002). Finally, reducing feed cultivation could provide an opportunity to expand the market for grass-fed animal production and for biofuels generated from cellulose, unfertilized cereals or grasses.

Addressing the Gulf of Mexico hypoxia problem may only be possible as part of an integrated program directed at consumers and agricultural producers. On the consumer side, policies encouraging diets with lower meat consumption could be tied to existing and proposed initiatives to reduce obesity and diet-related health concerns in North America. The annual US dietary guidelines have recently begun to stress the link between obesity, health and red meat consumption (US Department Health and Human Services (USDH), 2005). On the agricultural side, a change in the subsidy structure, forced in part by global trade negotiations, could begin to shift support from the larger industrial operations that focus on grain production for feed to smaller operations better suited to integrate cultivation of food crops with grazing animals. Incentives for reducing land devoted to feed cultivation an increasing area of riparian wetlands could be linked with established cropland abandonment programs like the Conservation Reserve Program, greenhouse gas reduction programs, and initiatives to restore native grasslands and waterfowl habitat in the central US. An integrated program like this could address several environmental and human health issues and set an important example for industrializing countries, like China, where meat consumption is expected to increase in the coming decades.

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